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Modeling cation exchange capacity in multi geochronological-derived alluvium soils: An approach based on soil depth intervals

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ABSTRACT

Knowledge of soil chemical properties is indispensable to conduct sustainable land use management in alluvial areas. In this study we developed specific pedotransfer functions for cation exchange capacity (CEC-PTFs) in alluvial soils based on soil depth intervals. A soil data set (n = 1094 samples) at different depths from three different Nile River terraces (lower, middle, and upper) and the lower and upper Blue Nile terraces in Sudan was randomly collected and divided into a training data set (n1 = 900 samples) and a testing data set (n2 = 194 samples) for validation. Soil pH, texture, and organic matter were used as predictor variables to estimate CEC. PTF performance was evaluated with the coefficient of determination (R^2), root mean square error (RMSE), and standard error for the estimate (SEE) between the observed and predicted values. Fourteen predictive equations were developed. Results revealed that the CEC of topsoil layers of the lower Nile River terrace were the most difficult to predict (r^2 = 0.29 for training) while the deep soil layers (60–120 cm) of the Blue Nile terraces were predicted well (r^2 = 0.99 for training). Sixty to 76% of CEC variation of the subsoil of the Nile River terraces could be explained by clay alone. From 85 to 90% of the CEC variation in the deep soils could be explained by organic matter, total silt, and total clay. Validated results indicate that the predictive models based on total clay were less reliable at predicting CEC in the top soil layers. Overall, the CEC-PTFs generated by multiple linear regression models (MLR) provided a reasonable estimate of CEC for most soils investigated.

1. Introduction

Soil cation exchange capacity (CEC) is important in agronomy, soil chemistry, and soil fertility (Khaledian et al., 2017a, 2017b). Despite this importance, there is a lack of global CEC datasets because traditional measurement is costly and time-consuming (Carpena et al., 1972; Fernando et al., 1977; McBratney et al., 2002; Amini et al., 2005; Budiman and Alfred, 2011).

There has been a recent emphasis on predicting unknown soil chemical properties using commonly measured properties. According to Viscarra et al. (2006), soil properties can be directly predicted by infrared absorption associated with functional groups, including organic carbon, total nitrogen, clay composition, soil CEC, and soil texture. However, as stated by Naes et al. (2002), soil properties can only be predicted if they fall within the calibration settings.

Numerous studies have attempted to develop pedotransfer functions (PTFs) to predict the CEC in various soils over the world. This has been accomplished using models that linked CEC to other soil properties using statistical tools such as multiple linear regression (MLR) (Bell and Van Keulen, 1995; Drake and Motto, 1982; Sahrawat, 1983; Yuan et al., 1967; Yukselen and Kaya, 2006; Olorunfemi et al., 2016), the combination of MLR and artificial neural networks (ANNs) (Bayat et al., 2014), of MLR, ANNs and adaptive neuro-fuzzy inference (ANFI) (Hadi et al., 2015), and more recently a combination of genetic expression programming (GEP) and multivariate adaptive regression splines (MARS) (Emamgolizadeh et al., 2015).

Despite the considerable progress in CEC prediction using the above-mentioned models, it appears that studies to develop CEC-PTFs for alluvial soils have not yet been conducted. This is attributed to the fundamental differences in the natural environmental conditions close to flood areas and specifically mechanisms of pedogenesis. Consequently, there are difficulties in CEC prediction in these soils

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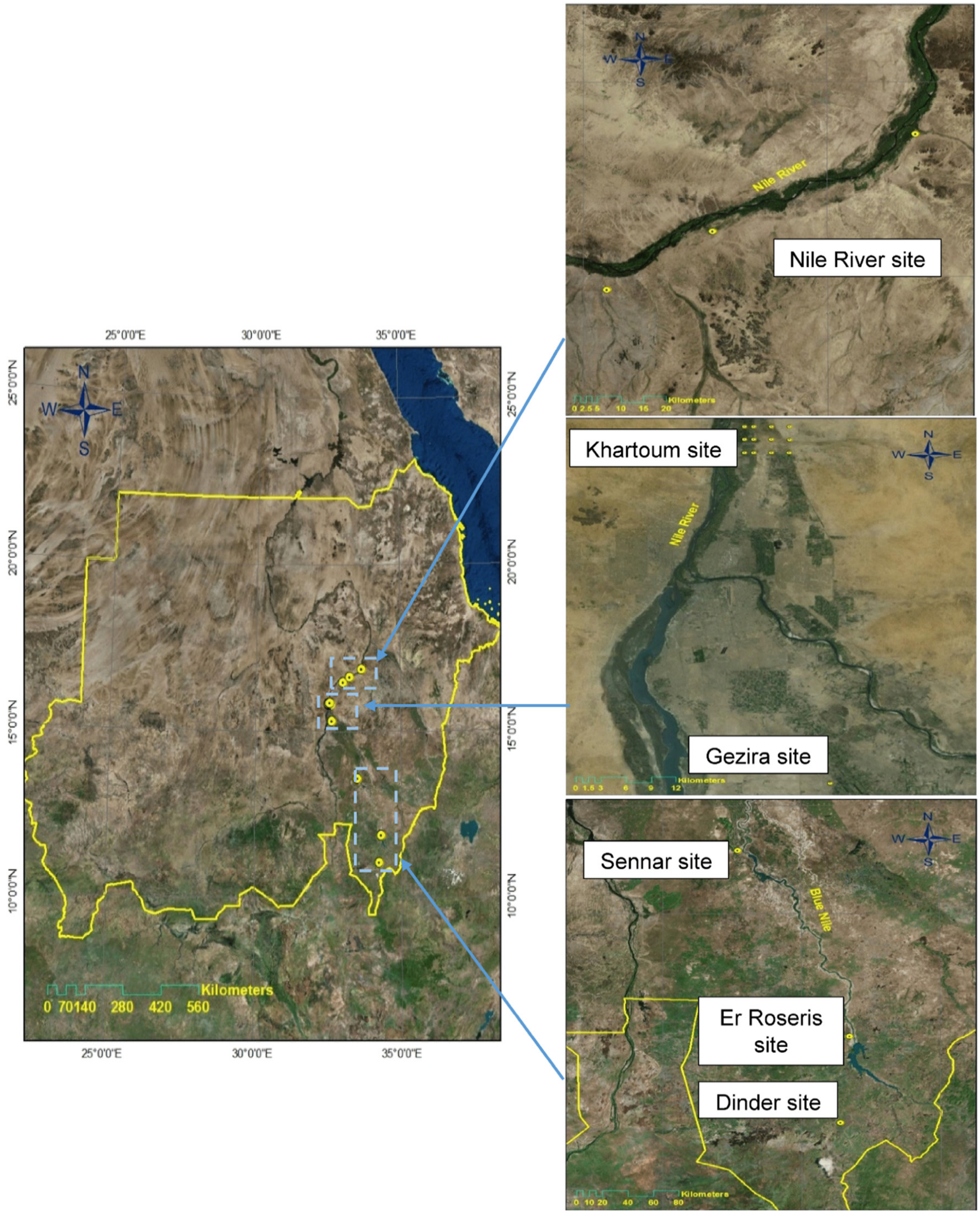

Fig. 1. The study area showing some of the selected profiles sites along the Nile River and Blue Nile.

using conventional pedotransfer functions.

Alluvial soils are widely used for intensive agricultural production around the world due to their high quality (Bertalan et al., 2016). However, non-suitable land use management can negatively affect soil properties and only well-planned decisions by farmers and policy makers can correct this situation (Lam et al., 2011; Acín-Carrera et al., 2013).

In Sudan, most of the irrigated intensive vegetable and fruit cropping areas are largely situated within the alluvial plains of the Blue Nile, White Nile, and River Nile terraces. Little research has been conducted on the soil properties of these terraces (Sulieman et al., 2016). Thus, this study seeks to develop pedotransfer functions to estimate the CEC in these alluvial soils based on soil depth intervals. The main aims of this study are to: (1) Test the hypothesis that the establishment of CEC-PTFs in alluvial soils based on soil depth intervals could provide a reasonable estimate of soil CEC; and, (2) develop CEC-PTFs models that work comprehensively for the alluvial soils in Sudan that could be applied in other research areas.

Soil pH, texture, and organic matter were the predictor variables used. The general performance of PTFs was evaluated based on the coefficient of determination (R^2), mean error (ME), root mean square error (RMSE), and standard error for the estimate (SEE) between the

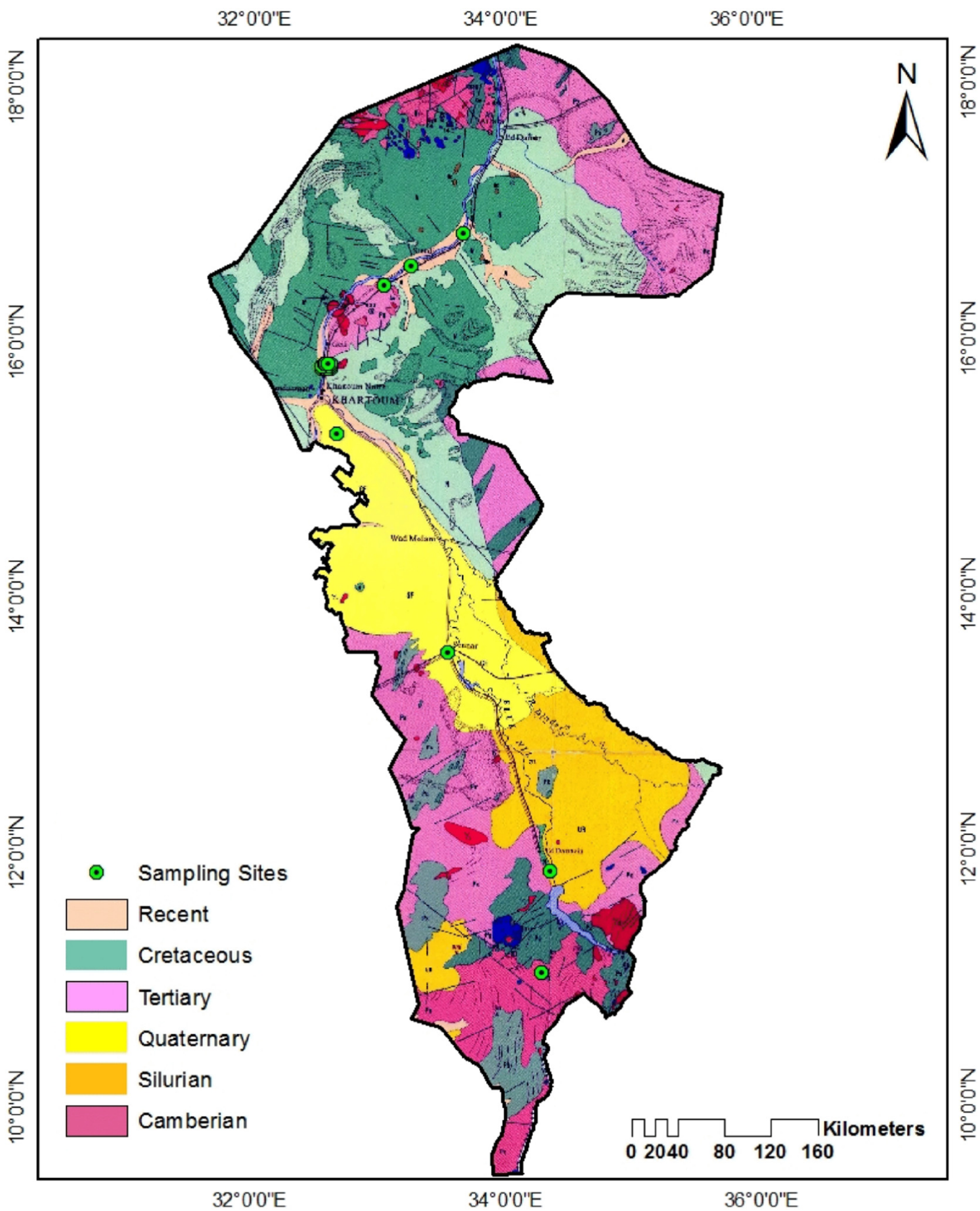

Fig. 2. Subset of the geological map of Sudan showing some of the selected profile locations in the study area.

observed and predicted values.

2. Materials and methods

2.1. Study area

A total of 1094 soil samples representing soils from across the upper, middle, and lower Nile River terraces and the upper and lower Blue Nile terraces in Sudan were collected and analyzed (Fig. 1). The soils on the Nile River terraces developed in transported, mixed-textured alluvial parent material, while fine to medium-textured alluvium parent materials are predominant in the soils of the Blue Nile terraces. The natural vegetation is variable along the Nile River and Blue Nile reflecting the low rainfall and high temperature conditions in the study area (Van der Kevie and El-Tom, 2004). According to the updated map of climatic classification (Peel et al., 2007), the climate of the study area is arid to semiarid, characterized by hot dry conditions for most periods of the year to relatively heavy rains during a short period in summers. The mean annual temperature varies from 28.3 to 29.6 °C and mean annual precipitation varies from 163 to > 700 mm (Van der Kevie, 1976). The soil profiles situated along Nile River in Khartoum City and Nile River State formed in the Nubian Sandstone Formation of the Cretaceous Period which comprises continental clastic sediments including sandstones, siltstones, mudstones and conglomerates (Fig. 2). Along the Blue Nile River, soils of the terraces are characterized by long-term climate-controlled weathering patterns on mainly igneous and metamorphic bedrock of the Ethiopian plateau (Sulieman et al., 2016). The soil profiles from Gezira State and Sennar belong to the Tertiary Gezira Formation, which is comprised of unconsolidated fine materials and gravels; whereas the El-Dinder and Er Roseires profiles

Table 1
Summary of descriptive statistics for measured soil properties of the lower and middle Nile terraces.

	Parameter	pH	TC[a]	TSi[b]	TS[c]	OM[d]	CEC
			%(m/m)	%(m/m)	%(m/m)	(%)	cmol kg^{-1}
Lower Nile terrace							
All soils (whole profile within 0–120 cm, n = 200)	Min	7.30	0.50	0.80	5.61	0.05	6.60
	Max	10.3	71.4	71.82	98.01	2.90	53.70
	Mean	8.22	26.79	28.51	44.80	0.58	30.10
	Std. dev.	0.61	19.84	21.11	29.43	0.68	11.06
	Skewness	1.61	0.61	0.44	0.51	1.82	0.20
	Kurtosis	3.54	−0.36	−1.14	−0.94	3.04	0.08
Topsoil (0–30 cm depth interval, n = 80)	Min	7.30	0.50	0.80	5.61	0.05	16.80
	Max	9.10	71.40	71.82	98.01	2.90	52.80
	Mean	8.03	21.98	31.32	46.99	0.63	32.53
	Std. dev.	0.38	20.22	24.25	32.12	0.68	7.72
	Skewness	0.43	0.71	0.24	0.58	1.69	0.87
	Kurtosis	0.37	−0.56	−1.52	−1.09	3.23	1.45
Subsoil (30–60 cm depth interval, n = 75)	Min	7.40	6.35	2.60	6.50	0.05	6.60
	Max	10.20	71.40	59.30	89.20	2.76	53.70
	Mean	8.36	31.47	26.80	41.58	0.55	25.99
	Std. dev.	0.69	19.77	19.15	29.36	0.76	15.20
	Skewness	1.10	0.67	0.34	0.52	2.26	0.48
	Kurtosis	1.80	−0.02	−1.33	−1.10	4.62	−0.62
Deep soil (60–120 cm depth interval, n = 45)	Min	7.68	14.50	7.00	9.10	0.07	13.70
	Max	10.30	67.40	51.00	77.10	1.93	50.50
	Mean	8.52	32.45	23.92	43.63	0.50	27.86
	Std. dev.	0.81	17.17	14.44	23.62	0.60	12.18
	Skewness	1.47	1.32	0.77	−0.23	1.76	0.90
	Kurtosis	1.63	0.68	1.15	−1.33	2.07	−0.40
Middle Nile terrace							
All soils (whole profile within 0–120 cm, n = 180)	Min	7.00	11.30	1.50	6.91	0.04	10.70
	Max	9.60	64.20	59.52	77.80	2.90	49.50
	Mean	8.15	29.18	18.45	52.40	0.71	23.63
	Std. dev.	0.90	12.37	14.15	20.33	0.87	9.40
	Skewness	0.45	1.35	1.27	−0.89	1.23	1.11
	Kurtosis	−1.32	1.82	0.97	−0.40	0.04	1.51
Topsoil (0–30 cm depth interval, n = 70)	Min	7.10	16.90	7.20	28.34	0.10	14.10
	Max	9.50	38.32	33.33	70.60	2.21	32.45
	Mean	8.22	24.88	16.35	58.70	0.60	21.77
	Std. dev.	0.90	6.66	10.31	12.88	0.79	5.95
	Skewness	0.13	1.10	1.01	−1.62	1.49	0.41
	Kurtosis	−1.75	0.70	−0.67	2.79	0.79	−0.62
Subsoil (30–60 cm depth interval, n = 65)	Min	7.00	11.30	1.50	6.91	0.04	12.40
	Max	9.60	64.20	59.52	77.80	2.34	49.50
	Mean	8.03	33.02	19.78	47.21	0.74	25.51
	Std. dev.	0.90	15.83	16.75	24.61	0.89	11.20
	Skewness	0.80	0.76	1.31	−0.44	1.15	1.13
	Kurtosis	−0.76	−0.13	0.89	−1.46	−0.49	0.88

[n] Number of samples.
[a] Total clay.
[b] Total silt.
[c] Total sand.
[d] Organic matter using the equation OM = 1.724 * OC.

are in the Quaternary Umm-Ruwaba Formation, which is comprised of unconsolidated sands with some gravels and shales (Ministry of Energy and Mines, 1981).

2.2. Data collection and stratification

Data to develop the CEC-PTFs were obtained from Buursink (1971) and Sulieman and Ibrahim (2013). The database contains > 450 soils locations with samples divided into topsoil layers (0–30 cm), subsoil layers (30–60 cm), and deep soil layers (60–120 cm) (total of 1094 soil samples) and representing soils from across the Nile River terraces on the upper, middle and lower parts, and the upper and lower Blue Nile terraces. The dataset was randomly divided into a training data set (N1 = 900 samples) for the development of CEC-PTFs using multiple linear regression (MLR) and a testing data set (N2 = 194 samples) for validation. The samples for training were distributed as follows: 343 samples from 0 to 30 cm, 334 samples from 30 to 60 cm, and 223 samples from 60 to 120 cm. For all soil datasets pH in saturated paste, soil texture by pipette method (Gee and Bauder, 2002), and organic carbon by modified Walkley-Black method (Nelson and Sommers, 1996) were analyzed. The CEC was determined by1 M NH_4OAc at pH 7 as described by Sparks et al. (1996). The soil database was partitioned into two homogeneous soil groups to improve the accuracy of CEC prediction. The first division of the dataset was based on the Nile terrace regardless of depth interval; the second division was based on the depth intervals in each Nile terrace. In the first division the training samples were distributed as follows: 200 samples from the lower Nile terrace, 180 samples from the middle Nile terrace, 160 samples from the upper Nile terrace, 190 samples from the lower Blue Nile terrace, and 170 samples from the upper Blue Nile terrace. In the second division the training samples were distributed as follows: 80 samples from the top layers (0–30 cm), 75 samples from the sub layers (30–60 cm), and 45 samples from the deep layers (60–120 cm) of the lower Nile terrace; 70 samples from the top layers, 65 samples from the sub layers,

Table 2
Summary of descriptive statistics for measured soil properties of the upper terrace.

Upper Nile terrace	Parameter	pH	TC[a]	TSi[b]	TS[c]	OM[d]	CEC
			%(m/m)	%(m/m)	%(m/m)	(%)	cmol kg^{-1}
All soils (whole profile within 0–120 cm, n = 160)	Min	7.00	7.00	3.70	6.91	0.03	5.70
	Max	10.20	62.70	59.52	87.00	3.31	35.80
	Mean	8.67	27.58	18.57	53.59	0.82	19.11
	Std. dev.	1.09	12.31	14.39	20.99	1.11	7.19
	Skewness	0.19	0.59	1.26	−0.36	1.30	0.12
	Kurtosis	−1.54	0.59	0.65	−0.47	0.09	−0.49
Topsoil (0–30 cm depth interval, n = 55)	Min	7.20	7.00	7.50	28.34	0.09	5.70
	Max	10.00	38.32	33.33	84.80	3.17	35.80
	Mean	8.69	25.85	17.16	57.00	0.68	19.09
	Std. dev.	1.00	10.53	9.34	15.52	1.11	8.69
	Skewness	0.06	−0.60	0.92	0.21	1.96	0.14
	Kurtosis	−1.52	−0.98	−0.65	0.47	2.49	−0.26
Subsoil (30–60 cm depth interval, n = 65)	Min	7.00	16.40	6.30	6.91	0.06	10.40
	Max	10.10	62.70	59.52	77.30	3.31	31.63
	Mean	8.51	32.46	20.62	46.20	0.93	20.86
	Std. dev.	1.06	13.36	17.50	21.78	1.17	6.18
	Skewness	0.50	1.06	1.28	−0.44	1.12	−0.22
	Kurtosis	−1.24	0.63	0.38	−0.81	−0.16	−0.30
Deep soil (60–120 cm depth interval, n = 40)	Min	7.10	9.30	3.70	21.20	0.03	10.00
	Max	10.20	40.70	43.00	87.00	2.90	27.07
	Mean	8.89	22.48	17.44	60.15	0.84	16.41
	Std. dev.	1.33	11.44	16.21	25.16	1.13	6.15
	Skewness	−0.16	0.43	1.01	−0.57	1.22	0.76
	Kurtosis	−2.21	−1.28	−0.88	−1.31	−0.19	−0.91

n Number of samples.
[a] Total clay.
[b] Total silt.
[c] Total sand.
[d] Organic matter using the equation OM = 1.724 * OC.

and 45 samples from the deep layers of the middle Nile terrace; 55 samples from the top layers, 65 samples from the sub layers, and 40 samples from the deep layers of the upper Nile terrace; 93 samples from the top layers, 67 samples from the sub layers, 30 samples from the deep layers of the lower Blue Nile terrace; and 45 samples from the top layers, 62 samples from the sub layers, and 63 samples from the deep layers of the upper Blue Nile terrace. A total of 194 samples were used for testing in both groups.

2.3. Model validation

An independent soil dataset was used to validate the models using 194 soil samples distributed as follows: 73 samples from the top-soils (30–60 cm), 71 samples from the sub-soils (30–60 cm), and 50 samples from the deep-soils (60–120 cm). Soil samples were randomly selected from the three different parts of the Nile River terraces and the two different levels of the Blue Nile terraces. Each homogeneous soil sample was run through the appropriate predictive model to estimate CEC in order to perform the validation step for all CEC-PTFs models using SPSS v.16 software (IBM, USA).

2.4. Statistical analyses

General statistical parameters such as minimum and maximum values, mean, standard deviations, median, mode, skewness, and kurtosis were calculated for each set of soil samples. Normality of the data set was examined by inspecting the skewness and kurtosis values of soil properties. Subsequently, Pearson linear correlation and regression analyses were conducted in two steps. The first step was to incorporate datasets from each Nile terrace regardless of the depth interval, and the second step involved handling the datasets separately for the various depth intervals in each Nile terrace. In both cases, multiple linear regression analysis was applied to model the pedotransfer function for the soil CEC (CEC-PTFs) using pH, total clay, total silt, total sand, and organic matter as predictor variables. The Pearson correlations were performed to determine variable collinearity and help in the selection of predictive variables (in this case the variable total sand was excluded from all equations). Only predictors that contributed 5% or more to the overall improvement of the coefficient of determination were included in the equations. All CEC-PTF models were evaluated based on six different error criteria, namely; the coefficient of determination (R^2), adjacent coefficient of determination (Adj.R2), mean error (ME), standard error for the estimate (SEE), root mean square error (RMSE), and normalized root mean square error (NRMSE) between the observed and predicted values. These six indices were calculated using the following equations:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (pred_i - \overline{obs})2}{\sum_{i=1}^{n} (obs_i - \overline{obs})2} \tag{1}$$

$$Adj\ R^2 = 1 - (1 - R^2)\,\frac{n - 1}{n - predi - 1} \tag{2}$$

$$ME = \frac{1}{n} \sum_{i=1}^{n} (obs_i - pred_i) \tag{3}$$

$$SEE = \frac{\sqrt{\sum (obsi - predi)2}}{n} \tag{4}$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (obs_i - pred_i)2} \tag{5}$$

$$NRMSE = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^{n} (obs_i - pred_i)2}}{\overline{obs_i}} \tag{6}$$

where n is the number of data points at i^{th} location; *obs* and *pred* are observed and predicted CEC values, and $\overline{obs_i}$ donates the mean for observed CEC values. The SEE gives the bias whereas RMSEE estimates the prediction accuracy (Verfaillie et al., 2006). After that

Table 3
Summary of descriptive statistics for measured soil properties of the lower and upper Blue Nile terraces.

Parameter	pH	TC[a]	TSi[b]	TS[c]	OM[d]	CEC
		%(m/m)	%(m/m)	%(m/m)	(%)	cmol kg^{-1}
Lower Blue Nile terrace						
All soils (whole profile within 0–120 cm, n = 190)						
Min	7.20	22.80	21.10	0.30	0.31	27.50
Max	9.10	71.40	77.20	43.20	1.41	53.70
Mean	8.05	41.59	43.64	14.73	0.68	40.07
Std. dev.	0.55	17.99	21.53	13.03	0.31	7.55
Skewness	0.31	0.78	0.23	0.85	0.87	0.68
Kurtosis	−0.86	−1.05	−1.89	−0.61	0.55	−0.52
Topsoil (0–30 cm depth interval, n = 93)						
Min	7.40	25.00	22.00	6.60	0.36	27.50
Max	9.10	71.40	65.00	43.20	1.41	52.80
Mean	8.08	39.54	35.86	24.60	0.32	36.74
Std. dev.	0.66	19.08	18.33	16.35	0.43	9.75
Skewness	1.02	1.61	1.33	−0.27	−0.08	1.44
Kurtosis	0.85	2.43	0.78	−2.63	−1.54	2.33
Subsoil (30–60 cm depth interval, n = 67)						
Min	7.20	22.30	21.10	0.50	0.32	35.40
Max	9.00	71.40	77.20	30.60	0.98	53.70
Mean	8.11	40.77	48.51	10.61	0.68	40.73
Std. dev.	0.58	18.43	23.91	11.61	0.23	7.09
Skewness	−0.13	1.011	−0.15	1.39	−0.47	1.51
Kurtosis	−1.02	−0.40	−2.33	0.40	−1.15	0.59
Deep soil (60–120 cm depth interval, n = 30)						
Min	7.40	25.30	22.50	0.30	0.31	35.20
Max	8.50	67.40	69.60	27.90	0.62	50.50
Mean	7.92	44.52	42.82	12.67	0.49	41.85
Std. dev.	0.47	19.41	21.76	9.07	0.14	6.65
Skewness	0.10	0.40	0.14	0.64	−0.52	0.46
Kurtosis	−2.61	−2.38	−2.87	1.68	−2.13	−2.19
Upper Blue Nile terrace						
All soils (whole soil profile within 0–120 cm, n = 170)						
Min	6.20	4.30	5.70	6.00	0.14	2.40
Max	9.00	76.50	23.50	98.10	1.33	72.00
Mean	7.76	52.81	16.36	31.62	0.55	45.55
Std. dev.	0.77	19.58	5.19	25.08	0.27	20.99
Skewness	−0.19	−1.09	−0.75	1.21	1.52	−0.57
Kurtosis	−1.10	0.14	−0.49	0.17	2.70	−0.64
Topsoil (0–30 cm depth interval, n = 45)						
Min	6.20	4.30	5.70	12.90	0.14	2.40
Max	8.00	68.90	23.50	89.00	1.33	70.90
Mean	7.11	47.04	16.70	36.19	0.75	43.23
Std. dev.	0.63	23.38	5.81	28.12	0.40	24.13
Skewness	0.40	−1.01	−1.20	1.19	0.16	−0.62
Kurtosis	−1.29	−0.30	0.66	0.22	−1.05	−0.46
Subsoil (30–60 cm depth interval, n = 62)						
Min	6.80	17.10	6.70	8.60	0.23	9.40
Max	8.70	73.90	21.30	89.10	0.64	72.00
Mean	7.88	53.89	15.46	32.07	0.49	45.73
Std. dev.	0.70	18.71	4.84	25.94	0.14	21.01
Skewness	−0.41	−1.05	−0.93	1.36	−0.89	−0.47
Kurtosis	−1.51	−0.05	−0.25	0.63	−0.52	−0.74
Deep soil (60–120 cm depth interval, n = 63)						
Min	7.00	17.90	8.70	6.00	0.31	11.50
Max	9.00	76.50	23.30	71.30	0.57	71.60
Mean	8.19	56.54	17.02	27.28	0.44	47.32
Std. dev.	0.62	17.32	5.30	22.63	0.10	19.64
Skewness	−0.29	−1.22	−0.51	1.24	0.08	−0.67
Kurtosis	−0.96	0.69	−1.29	0.07	−2.04	−0.53

n Number of samples.
[a] Total clay.
[b] Total silt.
[c] Total sand.
[d] Organic matter using the equation OM = 1.724 * OC.

multicollinearity and normality analyses were assessed for the regression analyses. Statistically significant differences were determined using $P \leq 0.05$. All statistical analyses were performed using SPSS software version 16 (IBM, USA) (SPSS Inc, 2018).

3. Results and discussions

3.1. Summary statistics of soil properties

A summary of the descriptive statistics for CEC, pH, total clay, total

Table 4
Pearson's correlation coefficients between soil CEC and predictors of the soils of Nile River and Blue Nile terraces.

Parameter	Lower Nile terrace				Middle Nile terrace				Upper Nile terrace			
	All	Topsoil	Subsoil	Deep soil	All	Topsoil	Subsoil	Deep soil	All	Topsoil	Subsoil	Deep soil
Cation exchange capacity (CEC)												
pH	−0.122 ns	0.14 ns	0.06 ns	−0.25 ns	−0.28 ns	−0.58*	−0.37	0.21 ns	0.07 ns	0.46 ns	0.26 ns	−0.65*
Total clay	0.61**	0.54**	0.95**	0.91**	0.71**	0.27 ns	0.78**	0.67*	0.50**	0.73**	0.08 ns	0.73**
Total silt	0.04 ns	−0.28 ns	0.20 ns	0.09 ns	0.35*	0.61*	0.15 ns	0.75*	0.34*	0.11 ns	0.42 ns	0.56*
Total sand	−0.44**	−0.13 ns	−0.77**	−0.72**	−0.68**	−0.62 ns	−0.6 ns	−0.91**	−0.53**	−0.56*	−0.4 ns	−0.69*
OM	−0.22*	−0.4**	−0.02 ns	−0.34 ns	0.35*	0.54*	0.14 ns	0.72*	0.25 ns	−0.2 ns	0.31 ns	0.92**

Parameter	Lower Blue Nile terrace				Upper Blue Nile terrace			
	All	Topsoil	Subsoil	Deep soil	All	Topsoil	Subsoil	Deep soil
Cation exchange capacity (CEC)								
pH	0.60*	0.88*	0.56ns	0.48ns	0.30*	0.91**	0.42ns	−0.42ns
Total clay	0.90**	0.94**	0.88**	0.99**	0.96**	0.97**	0.96**	0.96**
Total silt	−0.49*	−0.36ns	−0.56ns	−0.90**	0.73**	0.72**	0.80**	0.69**
Total sand	−0.43*	−0.69ns	−0.25ns	0.03ns	−0.80**	−0.96**	−0.93**	−0.58*
OM	−0.79**	−0.81*	−0.79**	−0.96**	0.26*	0.19 ns	0.72**	0.68**

ns non-significant.
* Correlation is significant at the 0.05 level.
** Correlation is significant at the 0.01 level.

Table 5
Modeling of soil cation exchange capacity (CEC) of the alluvium soils (based on depth intervals) using multiple-linear regression analysis.

Grouping	Linear Regression models	Observed	Predicted	R^2[a]	Adj. R^2[b]	SEE[c]	RMSE[d]	n[e]
Lower Nile terrace								
All soils	[0.341(In total clay) + 20.973]	30.104	30.113	0.37	0.36	8.82	8.69	200
Topsoil	[0.206(In total clay) + 28.009]	32.531	32.500	0.29	0.27	6.60	6.40	80
Subsoil	[0.645(In total clay) + 6.967]	27.266	25.786	0.76	0.74	7.44	7.96	75
Deep soil	[0.647(In total clay) + 6.876]	27.861	27.834	0.83	0.82	5.20	4.82	45
Upper Nile terrace								
All soils	[−2.262(In OM) + 0.213(In total silt) + 0.582(In total clay) + 4.329]	23.631	23.629	0.58	0.54	6.40	6.00	180
Topsoil	[2.224(In OM) + 0.259(In total silt) + 16.159]	21.770	21.778	0.44	0.27	5.07	4.24	70
Subsoil	[0.549(In total clay) + 7.394]	25.513	25.523	0.60	0.57	7.31	6.84	65
Deep soil	[−3.052(In OM) + 0.545(In total silt) + 0.875(In total clay) + 9.829]	22.196	21.886	0.85	0.74	4.81	19.15	45
Upper Nile terrace								
All soils	[0.116(In total silt) + 0.258(In total clay) − 8.522]	19.109	19.097	0.30	0.26	6.21	19.30	160
Topsoil	[0.602(In total clay) + 3.524]	19.096	19.108	0.53	0.49	6.20	5.71	55
Deep soil	[5.039(In OM) + 0.099(In total silt) − 0.084(In total clay) + 12.348]	16.411	16.424	0.89	0.82	2.64	1.96	40
Lower Blue Nile terrace								
All soils	[3.39(In pH) + 0.332(In total clay) − 1.025]	40.070	40.053	0.86	0.84	2.98	2.75	190
Topsoil	[0.349(In pH) + 4.547(In total clay) − 13.803]	36.740	36.752	0.91	0.82	4.10	–	93
Subsoil	[0.34(In total clay) + 26.847]	40.733	39.114	0.78	0.74	3.59	3.17	67
Deep soil	[0.341(In total clay) + 26.656]	41.850	41.822	0.994	0.992	0.58	0.48	30
Upper Blue Nile terrace								
All soils	[1.594(In pH) + 0.978(In total clay) + 0.084(In total silt) + 2.981(In OM) − 21.463]	45.547	50.450	0.91	0.90	6.51	6.06	170
Topsoil	[14.513(In pH) + 0.637(In total clay) + 0.264(In total silt) − 94.292]	43.227	43.078	0.99	0.988	2.64	2.20	45
Subsoil	[6.578(In pH) + 1.025(In total clay) − 0.026(In total silt) − 60.799]	45.729	45.713	0.96	0.95	4.83	5.57	62
Deep soil	[1.076(In total clay) + 0.245(In total silt) − 10.249(In total OM) − 13.157]	47.315	47.318	0.92	0.89	6.62	5.51	63

[a] Coefficient of determination.
[b] Adjacent coefficient of determination.
[c] Standard error for the estimate.
[d] Root mean square error.
[e] Number of samples.

silt, total sand, and OM for the Nile River and Blue Nile terraces are presented in Tables 1, 2, and 3. The mean total clay content was in most cases greater in the subsoil (30–60 cm) compared with the topsoil (0–30 cm) and deep soil (60–120 cm), with mean values ranging from 22 to 33% (*m/m*) in the alluvial soils of the Nile River terraces (Tables 1 and 2). In the alluvial soils of the upper and lower Blue Nile terraces the mean clay content was greater in the deep soil compared to the top soil and subsoil with mean values ranging from 40 to 57% (*m/m*) (Table 3). The mean values for total silt content for the sub-surface layers showed an irregular pattern across the soil profile, ranging from 15 to 48% (*m/m*). Contrary to the distribution of total clay and total silt, the mean for total sand content was always greater in the topsoil compared to the other depths, ranging from 25 to 59% (*m/m*).

The organic matter (OM) content was generally low in all soils and showed an irregular distribution through the soil profile. These trends in soil texture and OM content are in line with other alluvial soils as described by Aruleba and Ajayi (2013), who observed that soil OM content is commonly low in most arid environments. The highest CEC

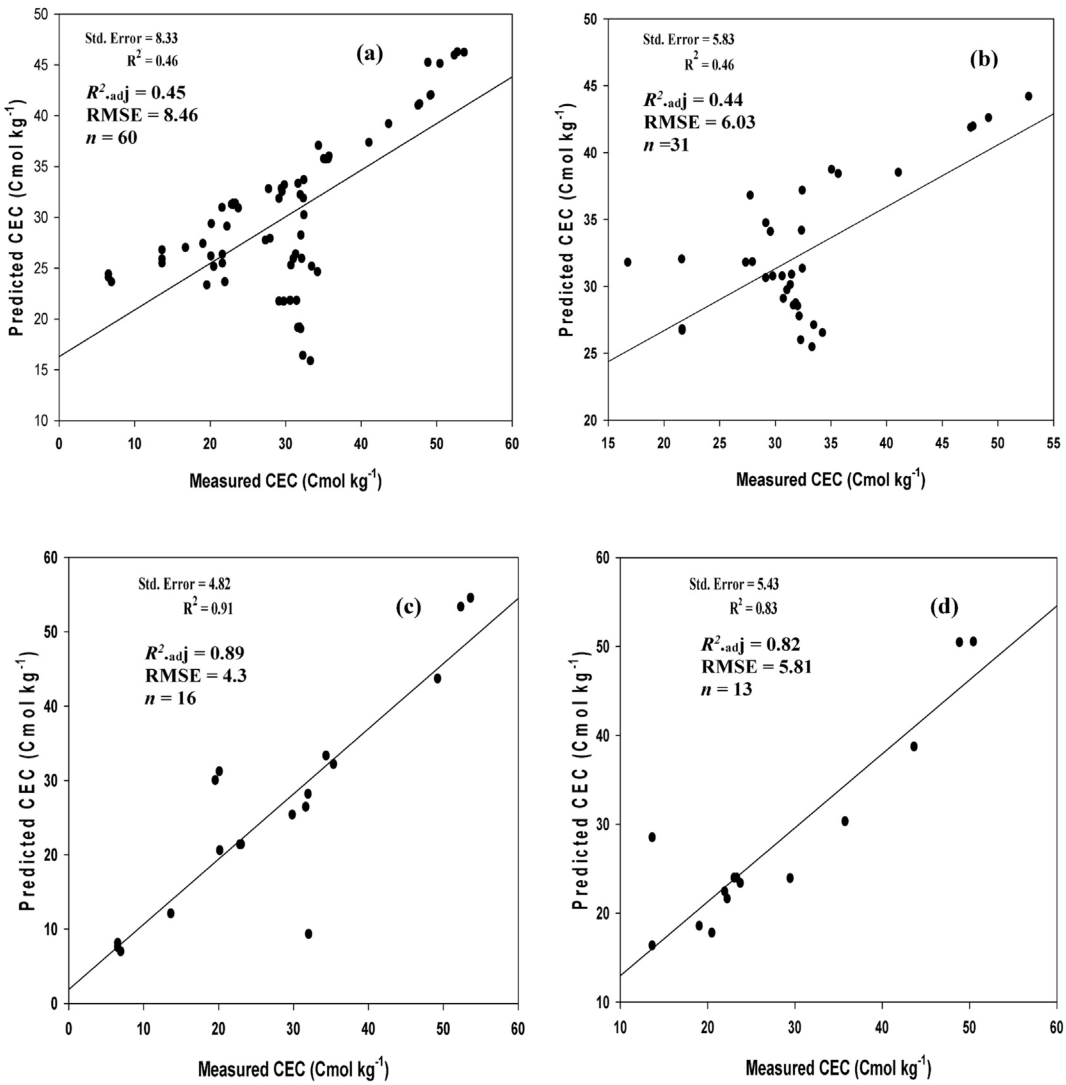

Fig. 3. Predicted versus measured values of soil CEC for the lower Nile terrace (a) all samples (b) topsoil (c) subsoil (d) deep soil.

means in the Nile River and Blue Nile terrace soils were recorded for the subsoils and deep soils, respectively; the highest CEC mean values were 33.02 cmol kg^{-1} and 56.54 cmol kg^{-1}, respectively. Several authors have confirmed that the CEC in most alluvial soils with high clay content in arid regions is largely controlled by the amount of clays, and therefore, mainly related to the domination of 2:1 clay minerals, precisely montmorillonite (Murthy et al., 1982; De Vos and Vigro, 1969; Chatterjee and Rathore, 1976).

3.2. Correlation of CEC with pH, particle-size distribution and organic matter

The Pearson's correlation results between CEC and pH, total clay, total silt, total sand, and OM are given in Table 4. A positive correlation between pH values and CEC was observed in the soils of the lower and upper Blue Nile terraces with R of 0.60 and 0.30, respectively. Our findings coincide with the positive correlations reported by other researchers in arid environments (Bell and Van Keulen, 1995; Bortoluzzi et al., 2006; Emamgolizadeh et al., 2015; Obalum et al., 2013; Krogh et al., 2000). Among all the soil variables studied, total clay content also showed a strong positive correlation with CEC at all depths in terraces. The strongest correlation was observed in the deep soil of the lower Blue Nile terrace with an R of 0.99. These results could be due to the domination of 2:1 clay minerals in these soils (montmorillonite), which are considered to be the major contributor to CEC in Sudanese alluvial soils (Buursink, 1971; Jewitt et al., 1979). Furthermore, this strong positive correlation between CEC and clay content is consistent with previous studies in several regions (Seybold et al., 2005; Amini et al., 2005; Elhagwa et al., 2007; Fooladmand, 2008; Saidi, 2012; Bayat et al., 2014; Kweon et al., 2012; Kashi et al., 2014). Significant positive correlations were also found between CEC and total silt for the middle and upper Nile River terraces and upper Blue Nile terrace. This is could be attributed to the presence of substantial amounts of 2:1 clay minerals in the silt fraction. The positive correlations between CEC and total silt are in accord with Buursink (1971), who reported that about 50% of the silt fraction in the Nile River and Blue Nile soils consists of minerals from the montmorillonite series, vermiculite series, kaolinite, and mica (in order of decreasing quantities). This high statistical correlation demonstrates the importance of developing soil protection measures to protect against hydrological processes that enhance soil pollutant transport and fine particle losses at the catchment scale (López-Vicente et al., 2016; Kavian et al., 2018). It is important to highlight that these soil protection measures should be carried out taking into account the farmer's perceptions and accounting for management strategies they are willing to accept. However, this situation is not commonly extended to farmers in non-developed countries (Biratu and Asmamaw, 2016; Nigussie et al., 2017).

A negative correlation between CEC and total silt was found in the

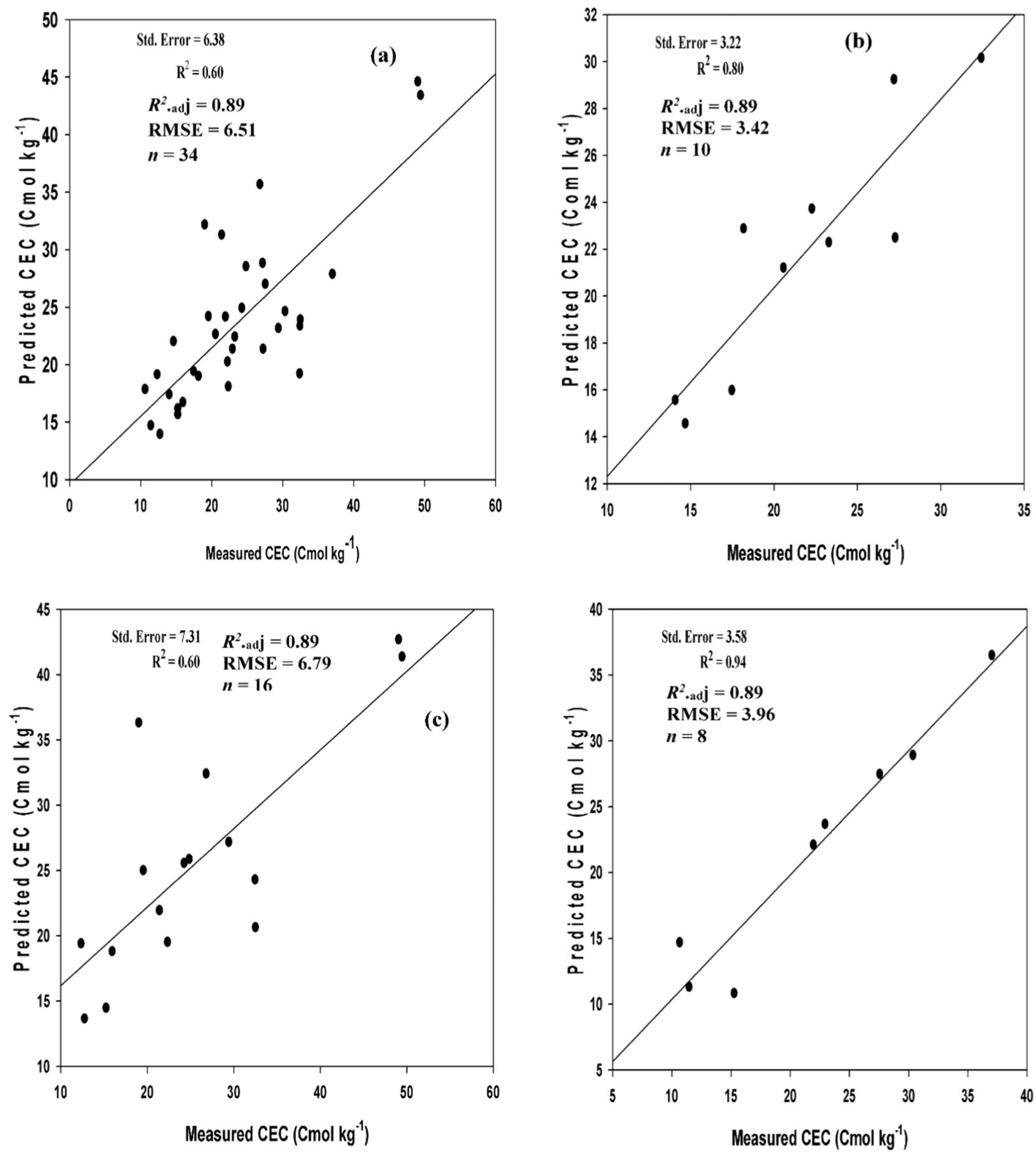

Fig. 4. Predicted versus measured values of soil CEC for the middle Nile terrace (a) all samples (b) topsoil (c) subsoil (d) deep soil.

topsoil layers of the lower Nile terrace, and topsoil, subsoil, and deep soil layers of the lower Blue Nile terrace. Correlations between CEC and total sand content are consistently strongly negative in all studied soils in all terraces. These results agree with several previous studies in arid regions such as Iran (Amini et al., 2005; Ersahin et al., 2006; Olorunfemi et al., 2016). The most striking result to emerge from the CEC relationships with the variables is the non-significant correlation ($P > 0.05$) between OM and CEC in most of the studied soils. A weak significant correlation ($P < 0.05$) between CEC and OM was only observed in the soils of the middle Nile terraces and upper Blue Nile terraces with R values of 0.35 and 0.26, respectively. Possibly, the intensive agricultural use or grazing and, subsequently, soil degradation processes have altered the soil parameters and as other researchers claimed, several difficulties to find coherent correlations can be registered (Bogunovic et al., 2017; Pulido et al., 2018) Our findings agree with Yukselen and Kaya (2006), Manrique et al. (1991), and Ohtsubo et al. (1983), who found non-significant to weak correlation of about 0.002, 0.12, and 0.27, respectively. Therefore, our finding is contrary to some other studies that have reported a strong correlation between CEC and OM in other areas (e.g. Seybold et al., 2005; Emamgolizadeh et al., 2015; Ghorbani et al., 2015).

3.3. Correlations between CEC and soil predictor parameters after partitioning the soil dataset based on depth intervals

Similar correlations were found between CEC and pH with a slight change in their correlations in the topsoil of the lower and upper Blue Nile terraces (Table 4). Their correlations are significant ($P < 0.05$) and produced R values of 0.60 and 0.30, respectively. The correlations between CEC and total clay were also highly significant ($P < 0.01$) for all soils of the lower Nile terrace ($R = 0.61$), middle Nile terrace ($R = 0.71$), upper Nile terrace ($R = 0.50$), lower Blue Nile terrace ($R = 0.90$), and upper Blue Nile terrace ($R = 0.96$). Data in Table 4 also indicate that basing the analyses on depth intervals significantly improved the correlations between CEC and total clay, in several cases yielding higher R values (e.g. the R value for the correlation in the upper Nile terrace soil increased from 0.61 for all soils to 0.95 for the subsurface soil and 0.91 for the deep soil). Findings were similar for the soils of the other terraces (Table 4). The stronger correlation between CEC and total clay in the subsoil as compared to the topsoil could be

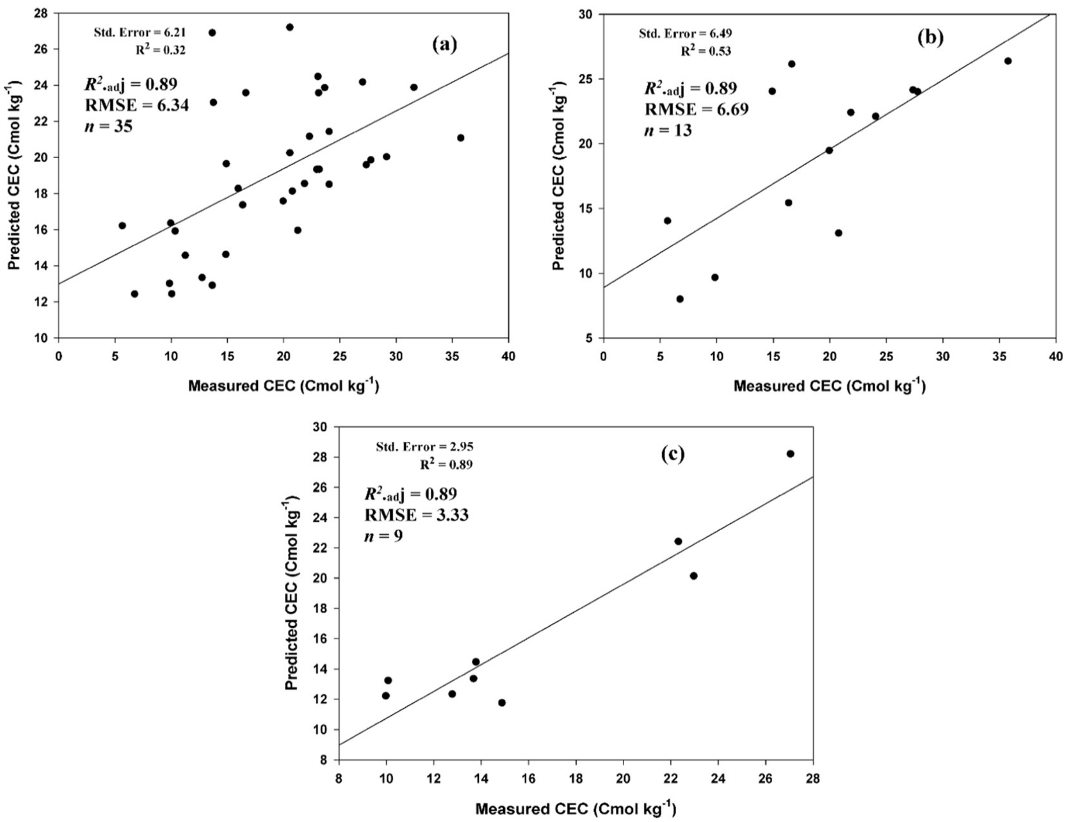

Fig. 5. Predicted versus measured values of soil CEC for the upper Nile terrace (a) all samples (b) topsoil (c) deep soil.

attributed to eluviation/illuviation processes (Torres-Sallan et al., 2017). The positive correlations between CEC and silt were weaker in the topsoil of the upper Blue Nile terrace and in the middle and upper parts of the Nile terraces when compared to the subsoil and deep soils. The most surprising correlation was the high positive correlation between CEC and OM in the subsoil and deep soil of the upper Blue Nile terrace (R = 0.72 and 0.68, respectively), and deep soil of the middle and upper Nile terraces (R = 0.72 and 0.92, respectively) in comparison with the weak correlations for the topsoil (R = 0.19, 0.54, and −0.2, respectively). These correlations are contrary to what would be expected in arid soils (strong correlation between CEC and OM in the topsoil as compared to the sub/deep soils). The logical explanation for these relationships from the pedology view of point could be attributed to the occurrence of soil layers rich in organic carbon at depth in the profile due to past deposition by the Nile River during flood events or when the climate was wetter than today. Thus, these soils now seem to be polygenetic and in equilibrium with the modern dry climate. Williams and Adamson (1974 and 1980) reported that there was a phase of very high flow in both the Blue Nile and White Nile from 11,500 to 11,000 years BP. This represents the early stages of Blue Nile; meanwhile the White Nile was up to 5 m higher than nowadays.

Vertical pedoturbation might be another main reason for the unexpected correlation between CEC and OM for the Blue Nile terraces. Kovda et al. (2010) studied the vertic processes (shrinking/swelling, lateral shearing and vertical turbation) and specificity of OM properties and distribution in Vertisols. They concluded that vertic processes affected the vertical and lateral distribution of soil organic matter (SOM) and its chemical and isotopic characteristics. Yaalon and Kalmar (1978) studied the dynamics of cracking and swelling clay soils, concluding that intrapedon turbations also play a slight role in changing the amount, distribution, and dynamics of soil organic matter in Vertisols. Pal et al. (2009) suggested that pedoturbation is a partially functional process in alluvial and clayey soils and thus it is not strong enough to overshadow the more significant long-term clay illuviation process.

3.4. Multilinear regression analysis (MRA) for CEC and soil property predictors

CEC was estimated for each data set using multilinear regression model procedures. Only data elements that contributed significantly to predicting CEC (from Table 4) were used in the regression equations, similar to the procedure followed by Asadu et al. (1997). For each equation the coefficient of determination (R^2), adjacent coefficient of determination (Adj.R^2), standard error for the estimate (SEE), root mean square error (RMSE), and normalized root mean square error (NRMSE) were calculated (Table 5). The CEC values for the topsoil of the lower and middle Nile River terraces were the least well predicted with R^2 values of 0.29 (RMSE = 6.40) and 0.44 (RMSE = 4.24), respectively. For the soils of the Blue Nile terraces, the subsoil CEC values of the lower Blue Nile terrace were the least well predicted with R^2 = 0.78 and RMSE = 3.17. Conversely, the deep soil and topsoil of the lower and upper Blue Nile terraces were predicted the best by the regression equations, both with R^2 values of 0.99 (RMSE = 0.48 and 2.20 respectively). Clay alone explained about 76% and 60% of the CEC variation in the subsoil of the upper and middle Nile River terraces, respectively. Combined, OM, total silt, and total clay explained about 85% to 90% of the CEC variation for the deep soils of the middle and lower Nile terraces. These three variables (OM, total silt, and total clay) account for about 92% of the variation in CEC for the deep soil of the upper Blue Nile terrace.

OM made the greatest contributions to CEC in the topsoil, while total clay made the greatest contribution in the subsoils (Table 5). These findings agree with Asadu and Akamigbo (1990) and Salehi et al. (2008), who indicated that the contribution of OM to CEC was considerably increased in topsoils as compared to subsoils. Table 5 also indicates that the application of linear regression models based on

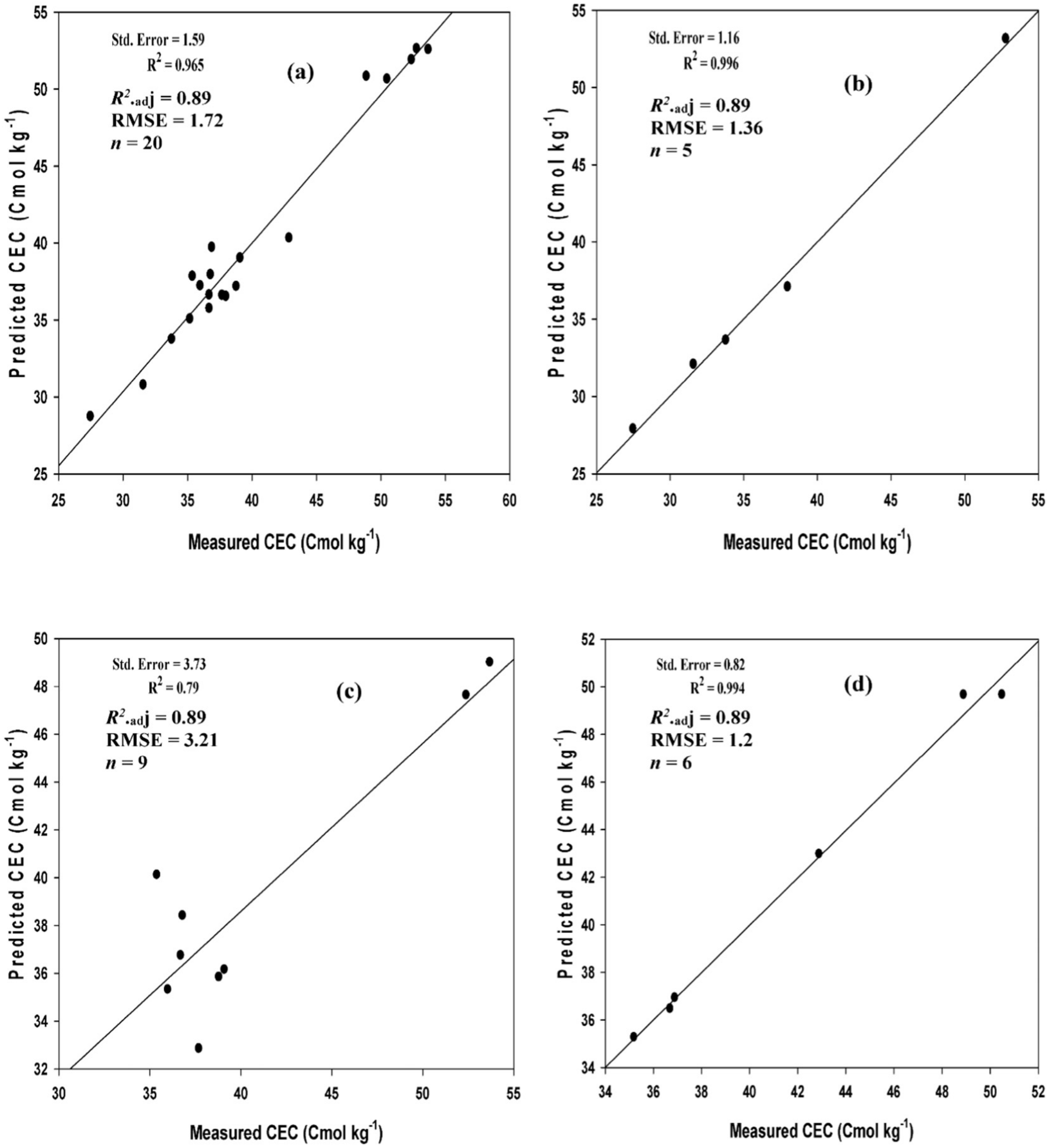

Fig. 6. Predicted versus measured values of soil CEC for the lower Blue Nile terrace (a) all samples (b) topsoil (c) subsoil (d) deep soil.

depth intervals resulted in improved CEC prediction in the alluvial soils of the Nile River terraces when compared to total profile predictions, thus the findings were more consistent. Obalum et al. (2013) studied the prediction of CEC for highly weathered and structurally contrasting tropical soils and concluded that partitioning the soils by layer depth improved the predictive ability of the CEC models and produced R^2 values between 0.71 and 0.76 in comparison with an R^2 value of 0.68 without partitioning by soil depth intervals.

3.5. Model validation

Scatter plots of the measured versus predicted CEC values for 194 soil samples from the three Nile River terraces and lower and upper Blue Nile terraces is shown in Figs. 3 through 6, respectively. All developed prediction models were used to perform the validation. The R^2 value increased from 0.46 to 0.80 for the top-soils of the three Nile River terraces when the organic matter and total silt were included and total clay excluded from the predictive equations. Results obtained show that the predictive models based on total clay are less reliable in predicting CEC in the top-soil layers of the alluvial soils considered here. On the contrary, total clay alone can provide a reasonable estimate of CEC in the deep layers of the alluvial soils ($R^2 = 0.83$), while the addition of OM and total silt to the models improves the CEC prediction, and as a result, increases the coefficient of determination ($R^2 = 0.94$). However, when total silt is included in the predictive equations, the R^2 decreases slightly from 0.996 to 0.993 for the top-soils of the Blue Nile terraces. This shows that the predictive models based on pH and total clay are overestimating CEC for these soils. On the other hand, for sub and deep soils of the Blue Nile terraces the clay alone proved less reliable in predicting CEC with R^2 values of 0.79 and 0.93, respectively. The addition of pH and total silt and total silt and OM to the predictive models, respectively, markedly improved the CEC prediction and the R^2 values increased to 0.97 and 0.99, respectively (Fig. 7).

4. Conclusions

A multiple linear regression (MLR) approach was used to develop pedotransfer functions (PTFs) to predict the CEC of the alluvium soils of three Nile River terraces and the lower and upper Blue Nile terraces in Sudan. Overall, 14 unique predictive equations were developed based on pH, total clay, total silt, and organic matter content as the predictor

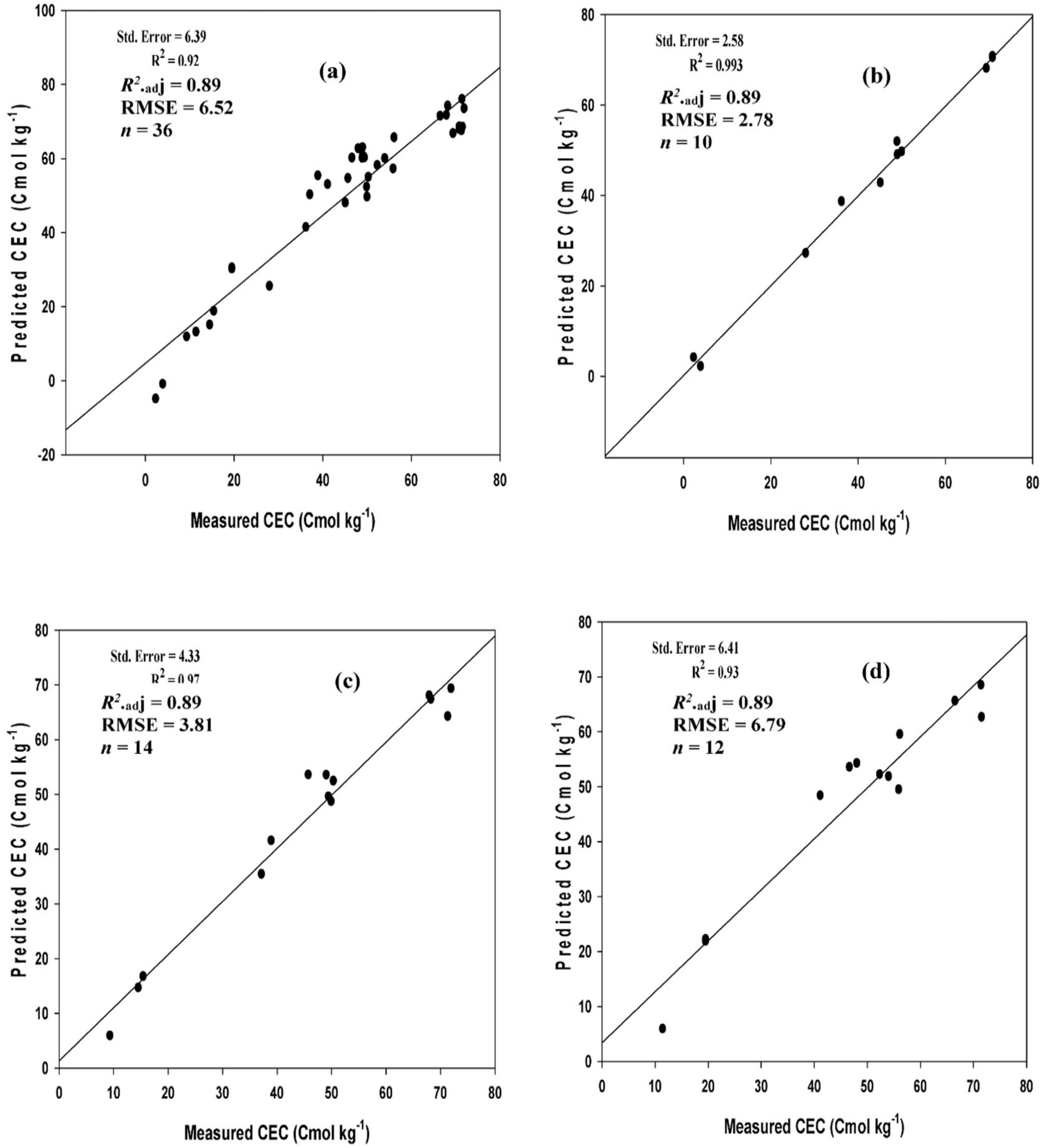

Fig. 7. Predicted versus measured values of soil CEC for the upper Blue Nile terrace (a) all samples (b) topsoil (c) subsoil (d) deep soil.

variables. The CEC-PTFs developed showed a reasonable CEC prediction accuracy. Validation of the findings indicated that the regression models in aggregate provided a reasonable estimate of CEC for the range of soils considered. Moreover, the obtained findings confirmed that MLR models based on depth intervals to estimate soil CEC can be a useful tool for land use management. This study is a first step towards the use of PTFs generated by multiple linear regression for CEC prediction in the alluvial soils along the Nile River. We recommend that future studies should aim to improve on the CEC-PTF predictive models using other statistical models instead of MLR to see if they provide better CEC estimates in these soils.

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